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(No)

MSC INTERNAL NOTE NO. 64-EG-5

PROJECT APOLLO

# AN ANALOG SIMULATION STUDY OF THE CONTROL OF LEM BODY TRANSLATIONAL VELOCITIES PRIOR TO TOUCHDOWN


Prepared by: ______________________
Clarke T. Hackler

Approved: K. J. Cox
K. J. Cox
Chief, Systems Analysis Branch

Approved: ______________________
Chief
Guidance and Control Division



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

March 9, 1964

# AN ANALOG SIMULATION STUDY OF THE CONTROL OF LEM BODY TRANSLATIONAL VELOCITIES PRIOR TO TOUCHDOWN

## SUMMARY

The control of touchdown velocities of the LEM vehicle during the final phases of lunar landing have been investigated in a six-degree-of-freedom simulation. A fixed-base simulator containing the pilot displays and controls was coupled to an analog solution of the equations of motion. Attitude control was afforded by a proto-type Gemini hand controller and main engine thrust and the RCS translational jets operated through an integrated controller similar to the controller now envisioned for the LEM vehicle. The attitude control system was operated in a rate command mode and employed on-off thruster logic.

The control task presented to the pilot was to land the vehicle within specified velocity limits starting from a set of given initial conditions. Pilot control of forward and lateral velocities was obtained by one of two methods: 1) rotation of the main engine thrust vector, and 2) thrusting with the RCS translational jets. Control of vertical velocity was accomplished through main engine thrust. The effect of control system parameters and RCS translational jet cross-coupling into the attitude control system on pilot performance was investigated.

The results of this study indicated: 1) that control of forward and lateral velocities just prior to touchdown can be effected as well using the RCS jets as using attitude rotation, although at increased RCS fuel expenditure, 2) the present control power of $6^{\circ}/sec^2$ afforded by a single couple approaches the lower limit for a satisfactory control system, but a double couple, which produces $12^{\circ}/sec^2$, provides satisfactory attitude control, 3) the cross-coupling of the RCS translational jets into the attitude control system is of sufficient magnitude to cause pilot control problems, 4) that it may be operationally unsound to operate the translational jets in the presence of c.g. offsets, and 5) the integrated main engine-RCS controller may cause pilot control problems when the RCS jets are operated unless a friction lock device of some type is designed into the controller.

## INTRODUCTION

The procedures for control of touchdown velocities of the LEM vehicle during the final phase of lunar landing is of interest at this time. There are several viewpoints as to the correct procedure for control of touchdown velocities. One viewpoint contends that position and velocity near touchdown are more controllable using the RCS translational jets, while the second believes the correct procedure is to use rotation of the main engine thrust vector.

Based on the results of a series of pilot-controlled simulations of the final phase of lunar landing conducted in-house and at NAA Columbus, it is believed that touchdown velocity control is best effected by rotation of the main engine thrust vector and that no requirement exists for using the RCS jets. The pilots flying these simulations did not state that the translational maneuvering capability of the LEM appeared to be restricted in any manner using thrust vector rotation. The problem of restricted cockpit visibility (one reason for using RCS jets) cannot be refuted directly since these simulations did not have an "out-the-window" capability. However, in this respect it must be noted that the maneuvering capability of the LEM is more restricted using the RCS jets because of the limited maximum thrust (200 pounds) available, which is roughly equivalent to an attitude rotation of 5 degrees. A thrust rotation of 15 degrees (the point at which the horizon disappears from view) provides almost three times the translational acceleration afforded by the RCS jets. Thus, with proper attitude response, precise velocity and translational control is theoretically better accomplished by thrust vector rotation.

To provide a satisfactory answer to the question of translational procedures, the Control Requirements Section, Systems Analysis Branch, has conducted a piloted simulation of the final phase of lunar landing. The primary objective of this simulation was to determine whether a requirement exists for using the RCS jets for translational maneuvers. A secondary objective was to determine if pilot control problems exist when using the integrated translational main engine thrust controller. This internal note discusses the velocity control procedures and the results of the simulation.

## DESCRIPTION OF SIMULATION

The simulation of the final portion of the lunar landing was accomplished by coupling an analog solution of the 6 DOF equations of motion to a fixed base LEM cockpit containing the pilot displays and controllers. The equations of motion assumed a flat "moon" (no orbital terms) because of the low translational velocities associated with the problem. Attitude control was effected by a three-axis hand controller similar to the Gemini controller. Main engine thrust control and control of the two translational axes (horizontal and lateral) were by means of an integrated controller essentially similar in action to that presently proposed for the LEM vehicle. Displays provided the pilot included: 1) three-axis eight ball for attitude, 2) altitude and altitude rate with respect to local vertical, 3) body translational velocities ($\dot{x}$ and $\dot{y}$ for this simulation, but $\dot{z}$ and $\dot{y}$, respectively, with respect to actual LEM body axis system), 4) engine thrust to weight ratio, 5) body angular rates, and 6) a simulated radar display (PPI) of the target location on a 5 inch CRT. The attitude control system employed on-off thruster logic with an adjustable deadband and control moments and was operated in a rate command mode. Provisions were incorporated in the LEM body equations for cross coupling effects of the translational jets into the body rotational motion equations. Because of time limitations, center-of-gravity offsets were not provided for in the simulation. Vehicle characteristics (mass, inertias, etc.) were approximately those of the current LEM spacecraft.

## Control Task

The initial control task given to the pilots was to translate the LEM to a preselected landing site and land within a given set of constraints. The second control task was to reduce the translational velocities and land without regard to the actual landing site location. The translation was to be done by a) rotating the main engine thrust vector and b) thrusting with the RCS jets. Ground rules for translating and landing were that the LEM attitudes should not exceed ±15 degrees during translation and be as near zero as possible at touchdown. The acceptable horizontal and lateral velocities were to be less than ±5 feet/second, the vertical velocity less than 10 feet/second at touchdown. The initial conditions for the study were:

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|---|---|
| Downrange | 100 feet |
| Crossrange | 0 feet |
| Longitudinal velocity ($\dot{x}$) | 10 feet/second |
| Lateral velocity ($\dot{y}$) | 0 feet/second |
| Vertical velocity ($\dot{h}$) | -5 feet/second |

From these initial conditions, it is readily apparent that the area of investigation comprised an extremely small portion of the total landing control task. However, it is precisely in this area where the final corrections in velocity and position must be made prior to touchdown. The results of this simulation as discussed below must be considered in their proper perspective to the overall control task confronting the pilot during the total lunar landing mission.

Test subjects used in this simulation included three rated pilots from FCSD and one astronaut. Two other astronauts flew the simulation but did not participate as subjects. A total of 103 recorded data runs were made, divided about equally between the two translation techniques.

## DISCUSSION OF TEST RESULTS

The first control task was to translate and land the LEM at a preselected landing site using the radar display. An examination of the data resulting from the tests indicated no appreciable difference in touchdown conditions for the two techniques. The velocities at touchdown were well within the ground rules for $\dot{x}$ and $\dot{y}$ (both less than 0.8 feet/second) and less than -8.3 feet/second for $\dot{h}$, also within requirements. The absolute displacement error at touchdown was somewhat better for the RCS jets than attitude rotation (6.8 to 10.2 feet) but this does not appear to be extremely significant. The total $\Delta$V expenditure was higher (158 to 139 feet/second) for the RCS, probably because the pilots tended to try for better position accuracy which increased the maneuver time, although some of this increase may be due to thruster firing alone. The extremely low touchdown velocities in $\dot{x}$ and $\dot{y}$ are conditioned by the fine resolution displays used in the simulation. It is doubtful the pilot can control velocities this accurately in the real world because of visual discriminatory limitations at the distance he must obtain velocity cues (approximately 30' from his eye). The pilots had no particular difficulty in performing the task with either technique, but better pilot control of velocity was afforded by the RCS jets because of the sluggish response of the attitude control system. The gross velocity changes were faster with thrust vector rotation because of the higher translational acceleration. However, because of the low control power (torque to inertia ratio), the correction of low magnitude velocities was more difficult, although the touchdown velocities were approximately the same regardless of technique.

The second control task was to reduce the translational velocities to the ground rule limits and land without regard to the landing site location. The pilots performed this task somewhat more easily than when using the radar display because of the reduced display scan required to complete the maneuver. Touchdown velocities were roughly equivalent to those obtained for the first control task, but the $\Delta$V expenditure was about equal (120 feet/sec) for both techniques. The decrease in $\Delta$V was due to the decreased maneuver time, which was roughly the same for both maneuvers. The pilots were again inclined to favor the translational jets for the reasons stated above.

The ground rules for landing were changed so that the vertical ($\dot{h}$) touchdown velocity was to be less than 5 feet/second. In addition to this, the pilots were to have the engine at idle cut off at touchdown since this will be an operational requirement necessary for vehicle stability. In this case, the pilots landed the vehicle within the velocity requirements (-3.3 and -3.7 feet/sec for jets and thrust vector rotation, respectively), but the $\Delta$V expenditure rose to 166 feet/sec for the RCS jet maneuver and 127 feet/sec for the thrust vector rotation maneuver. The increased $\Delta$V expenditure for both techniques was due to the slightly increased maneuver time which can be attributed directly to the decreased descent velocities. The significantly increased $\Delta$V expenditure in the RCS jet maneuver was probably due to mechanical interface problems associated with operating the translational controller and main engine throttle simultaneously. The problem existed for the 10 feet/second ground rule, but the higher allowable touchdown velocities did not make it so acute. The pilots, as a rule, tended to counteract the interface by pressing their left knee against the integrated controller thus providing friction of a sort. While the controller was not identical to the one currently proposed by GAEC, it is similar enough in design to indicate a friction lock device of some type should probably be incorporated. However, a series of tests should be made on the prototype design to determine if a friction device is an absolute requirement.

Variation of Control System Parameters

The effect of various control parameters on pilot performance was also investigated. These parameters included control power, rate deadband limit, and control mode. Results of these parameters variations are summarized below:

a. Control Power - The present LEM attitude control power of $6^{\circ}/sec^2$ proved adequate for performing the translational maneuver providing rapid changes in altitude were not commanded. If the pilots did call for attitude changes in the order of 12 to 15 degrees, they were required to anticipate rate cut-off relatively early to prevent overshooting the desired attitude. Overcontrol of attitude due to the low control power during translation maneuvers caused difficulty in achieving the desired velocities because of the sluggish vehicle response in attitude.

Cross coupling of the translational jets into the attitude system also caused control problems because of the large moment arms of the RCS jets about the c.g. Firing of the translational jets in the present vehicle results in an angular acceleration of almost 3.4 deg/sec$^2$, equal to 57% of the attitude control power. The attitude control of the LEM during RCS jet firing, then, is a two-level operation in that altitude changes in one direction have an angular acceleration of 9.4 deg/sec$^2$ and in the other direction have an acceleration of only 2.6 deg/sec$^2$. This presents no problem so long as small attitude changes occur during RCS jet firing, but any large altitude changes would probably lead to an uncontrollable situation.

Increasing the control power to 12 deg/sec$^2$ eliminated some of the undesirable features of translation by thrust vector rotation since the vehicle attitude response to control inputs was much better. The two level operating effect was still present, but was fairly well masked by the 12 deg/sec$^2$ control power. Results of the runs showed that the increased control power did not affect terminal velocities or fuel consumption appreciably. However, the test subjects had less trouble controlling altitude and translational velocities during the maneuver and also tended to shift their opinion as to the effectiveness of thrust vector rotation.

b. Control Mode - Change of the control mode from rate command to the direct mode failed to affect the test results to any large extent. The translational velocities at touchdown were less than 1.0 feet/sec, but the vertical touchdown velocity was about -5.3 feet/sec higher for the direct mode, or just slightly over the ground rule limits. The $\Delta V$ expenditure, however, was significantly less for the RCS jet maneuver in direct than for the same maneuver in rate command (135 to 166 feet/sec, respectively). This reduction was almost certainly due to the pilots landing the vehicle as rapidly as possible when thrusting with the RCS jets because of the strong cross coupling effect the jets had on the attitude control system.

c. Deadband - The attitude control system was varied from essentially zero to 2 deg/sec. The major result of deadband was to reduce the effect of the RCS translation jet cross-coupling into the attitude control system. A deadband of zero degrees (a physically impossible condition) completely eliminated the cross coupling since the automatic features of the control system reduced to zero all rates due to cross coupling. A 2 deg/sec deadband resulted in a practically uncontrollable vehicle whenever the translation jets were operated. The pilots could fly and land the vehicle, but with extreme difficulty and without being able to attain consistent terminal conditions. A rate deadband of 0.5 deg/sec provided an easily controllable vehicle that could be handled without large side effects occuring during RCS firing. The 0.5 deg/sec rate caused by RCS jets caused a noticeable attitude change, but this presented no piloting problems providing the pilots maintained fairly tight attitude control.

## Translational Jet Cross-Coupling

Cross-coupling of the translational jets into the attitude system caused no difficulty unless the rate deadband was too wide or the attitude control mode was in direct thruster operation. In fact, because the attitude change during RCS jet thrusting is always in the direction to assist the RCS jets in changing velocity, the effective acceleration of the jets is increased by an amount proportional to the attitude change. This, however, did not influence the test results for the pilots were required to maintain a near zero attitude during RCS thrusting. The major effect of cross-coupling is that of attitude fuel consumption since the attitude jets must operate anytime the body rate exceeds the deadband limit. As noted before, the angular acceleration caused by the RCS jets is 3.4 deg/sec$^2$ which means the rate deadband limit will be exceeded practically every time the RCS jets are fired. This is operationally objectionable since the RCS fuel is obtained from the ascent tanks. It appears, then, that a trade-off between any possible ease of LEM translation with the RCS jets and ascent tank fuel usage must be made.

## Center-of-Gravity Offset

Time limitations of the study precluded examination of the effect of center-of-gravity offsets on pilot performance. However, the effect of c.g. offset uncertainties on pilot control and vehicle performance are readily hypothesized. Assume the c.g. offset causes a roll angle of 2 degrees and that the engine thrust level during the translation is 2100 lunar pounds. This offset and engine thrust results in a side force of about 70 pounds if the vehicle roll angle is maintained at zero degrees according to the eight ball. Hence, the available force for translating in one direction is 270 pounds whereas only 130 pounds for translating in the opposite direction. This means that if the pilot translates laterally in the direction of the 270 pound thrust capability it requires over twice as long to reduce the velocity to zero as it required to attain the velocity. This will be confusing to the pilot and can quite possibly lead to operationally unsound maneuvers. Another problem associated with c.g. offset is that unless the vehicle is rolled (for the above case) to compensate for the lateral side thrust, the pilot will be required to continuously operate the RCS jets in an on-off manner to prevent lateral translation. Translation by attitude rotation results in a similar condition although the c.g. offset effect is not as pronounced. Using the same assumptions as before, if an attitude change of 10 degrees is commanded, the actual attitude attained will be 12 degrees in one direction and 8 degrees for the opposite rotation. Hence, if a velocity is built up in the 12 degree direction, it requires 50 percent longer to reduce it in the 8 degree rotation. This is no more desirable than in the translation with the RCS jets, but it is certainly much less objectionable from the viewpoint of piloting procedures. Actually, the effect of c.g. offset is compensated almost automatically by the pilot since vehicle attitude is used to correct velocity. The pilot, in other words, does not care what the attitude is as long as it remains within reasonable limits. Operationally, then, the pilot control problems are much less severe in the presence of c.g. offset uncertainties using thrust vector rotation for translation near the lunar surface.

## CONCLUSIONS

The following conclusions are made based on the results of this study:

1. Control of the forward and lateral velocities of the LEM just prior to landing touchdown can be effected as well using the RCS jets as using attitude rotation. However, the runs in which the RCS jets were utilized resulted in greater expenditure of fuel.

2. The present attitude control power using a single couple (2 jets) and producing about 6 deg/sec$^2$ is approaching the lower limit for a satisfactory control system. The control power associated with a double couple (4 jets) provides satisfactory control.

3. The cross-coupling of the translational jets into the attitude control system is of sufficient magnitude to cause pilot control problems if a) the rate deadband is too wide, and b) if the attitude control mode is in direct thruster operation. In addition, the cross-coupling will cause excessive attitude fuel consumption in the presence of narrow rate (and attitude) deadbands.

4. It appears that it may be operationally unsound to attempt translational maneuvers with the RCS jets in the presence of c.g. offsets. However, this hypothesis should be verified by actual simulation to determine if the pilot can compensate for the effect caused by c.g. offset uncertainties.

5. There is a distinct possibility that the integrated controller will cause pilot control problems when the translational jets are operated unless a friction device of some type is incorporated into the main engine throttle portion of the controller.